Equitable Transit Futures: The Distribution of Benefits of a Proposed Rapid Transit Line in Toronto

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ABSTRACT

Assessing whether the benefits of proposed public transit projects are fairly distributed across population groups is increasingly becoming an important part of transit planning practice. In this paper, we outline and exemplify a procedure for evaluating the equity impacts of a new transit line. Specifically, this procedure incorporates census-based socio-economic data and the output of travel demand models to examine the distribution of benefits across a comprehensive set of outcomes: access to transit stations, access to destinations by transit, travel times, and transit travel demand. This procedure is focused on low-income and other low-SES populations who arguably have the greatest need for transit improvements. Importantly, our procedure incorporates a sensitivity analysis to account for the possibility of increased income segregation or transit-induced gentrification on future equity outcomes of the transit line. This is exemplified for the Ontario Line, a proposed rapid transit project in Toronto, Canada. The main finding, consistent across most facets of the analysis, is that the benefits of the Ontario Line are forecasted to be fairly evenly spread across all levels of socioeconomic status in the region, with modest concentrations specifically among low-income populations.

INTRODUCTION

Major public transit investments, such as new rapid transit lines, provide a wide range of benefits for urban residents such as reduced travel times, improved ability to access daily activities such as employment and education, as well as greater propensity to curb costly and unsustainable auto-oriented lifestyles. However, there are increasing concerns among transport planners and researchers regarding whether existing and future transport networks are distributed equitably across different population groups (1,2), a concern that is increasingly raising ethical flags among transit planners, activists, and academics alike (3,4).

In this paper, we outline and exemplify an evaluation procedure for assessing how the benefits of proposed transit investments are distributed across different population groups. This procedure is designed to evaluate a comprehensive set of outcomes, and can be used to accompany or compliment traditional transit planning documents such as initial business cases. This procedure is based on travel demand model outputs which are often generated when evaluating proposed transit infrastructure, specifically future travel time and flow matrices. We show how these data can be analyzed in conjunction with commonly available land use and census based socio-economic data to examine the distributions of transit benefits across the following four dimensions, the first two of which represent changes in opportunity, while the second two represent changes in outcomes.

1. Improved access to rapid transit stations.
2. Improved access to destinations by transit including gains in access to education, employment, and low-income employment.
3. Reduction in travel times.
4. Increased transit travel demand.

We exemplify this procedure by analyzing the distribution of these benefits stemming from the Ontario Line (OL), a proposed rapid transit line in Toronto, Canada (5). Specifically, we compare the OL to a do-nothing scenario, while carefully disaggregating the estimated benefits of the OL line by socioeconomic groups most relevant to disadvantage in the GTHA: unemployment, poverty, visible minority, and recent immigration. We also provide a sensitivity analysis of our results based on whether or not there will be continuing trends of income segregation as well as the possibility of transit-induced gentrification. The results are presented in a series of descriptive maps and data visualizations. The main finding of our case study, consistent across most facets of the analysis, is that the benefits of the OL are forecasted to be fairly evenly spread across all levels of socioeconomic status in the region, with modest concentrations specifically among lower-SES groups, particularly those below the poverty line. In other words, we find the distribution of benefits to be vertically equitable, in that they concentrate among population groups more likely to depend on public transit for their daily mobility needs relative to the overall population. However, this will not be the case if gentrification occurs in areas of relatively higher transit accessibility causing a substantial spatial re-distribution of low-income households to concentrate in less accessible neighbourhoods.

BACKGROUND & MOTIVATION

New public transit infrastructure can provide a number of societal, economic, and environmental benefits. These include, but are not limited to, decreased travel times and increased comfort for existing riders (6), providing people the opportunity to access and participate in more daily activities (7), promote denser and more sustainable land development at transit stations (8), and reduce auto-based travel and its associated environmental impacts (9). Benefits of proposed infrastructure are often quantified (e.g. as minutes of travel time saved, or number of new trips generated) and then weighed against the capital and operating costs to evaluate whether or not a project should be constructed. These evaluations often take the form of a Cost Benefit Analysis (CBA) or multi-criteria decision analysis in order to assess one or more infrastructure proposals, often in relation to a do-nothing (i.e. business as usual) scenario (10).

Potential benefits of proposed rapid transit are typically assessed via averaging across the population. However, planning agencies in some nations have legal responsibility to prohibit the discrimination of government project funding, such as funding for public transit projects. For example, in the United States, this is covered by Title VI of the 1964 Civil Rights Act, and in the UK, the 2010 Equality Act and the 2011 Public Sector Equality Duty (1,11). Regardless of legal requirements, many have called for increased consideration of how the costs and benefits of the outcomes of transport plans are distributed across different socioeconomic groups (2,12,13). This stems from a wide body of research which has shown that transport disadvantage, such low levels of transit accessibility, can compound with social disadvantage (e.g. low income) to increase risks of social exclusion (14). As such, many argue that public transit projects should be prioritized towards neighbourhoods with high prevalence of poverty and social deprivation as people in these neighbourhoods are more likely to be reliant on public transit to access and participate in daily activities necessary for their livelihoods and well-being (2), and that these considerations should be considered at the early stages of transportation planning processes (13).

The simplest way to examine how the benefits of new transit infrastructure are distributed demographically is to overlay on a map the location of the proposed plan in relation to socioeconomic census data. This can be expanded to creating a walking buffer around transit stops and analyzing the population distributions in relation to these buffers (15), comparing before and after transit improvement scenarios. For example, Teunissen et al., (16) found that increase in access to BRT stations in Bogota were evenly spread across socio-economic groups. In another study, Farber & Grandez (17) examined the socio-economic need of planned LRT stations in the Toronto region finding that new routes consist of stations at both ends of the socio-economic spectrum.

A more comprehensive way to measure public transit service are metrics of transit accessibility, which can be summarized as the ease of reaching activity destinations by public transit (18,19). Several studies have examined how the spatial distributions of transit accessibility are related to socio-economic attributes in order to assess the equity of transit provision (20,21,22,23), or to analyze their combined effects on outcomes such as employment (24) or commuting times (25). There are also several studies which have analyzed, in retrospect, how the relationships between transport accessibility and socio-economic status change over time in a region (26,27,28).

Fewer studies, however, have examined how the socioeconomic distribution of transit accessibility would change given the completion of proposed or under construction transit network expansions. In Montreal, Manaugh & El Geneidy (29), examined before and after accessibility changes for planned transit network developments, with a focus on socially disadvantaged neighbourhoods. They found that overall, disadvantaged neigbourhoods benefited more relative to non-disadvantaged neighbourhoods. However, there were still some disadvantaged neighbourhoods which received little benefit. In Toronto, Farber & Grandez (17) examined accessibility change specifically in transit station catchment areas of new transit lines, finding a needs mismatch where stations which will witness the biggest gains in accessibility are not those of high socioeconomic priority. In the Twin Cities, Guthrie et al., (30) examined change in accessibility before and after several proposed rail and BRT projects, showing improved accessibility for disadvantaged neigbhourhoods. In Rio de Janeiro, Pereira (31) examined how new BRT infrastructure will alter employment accessibility for different income levels, testing different types of cumulative accessibility formulations. Gains in accessibility were found to be equitable or focused towards low-income households, depending on the accessibility measure used.

The aforementioned research focused on changes in accessibility, which in general is a measure of opportunity or freedom to be able to participate in daily activities. However, there has been much less research focusing on the socio-economic distributions of potential travel behavior outcomes stemming from proposed transit improvements. Travel times are one such outcome that have been cited as important when analyzing the inequality of transport systems (32). Some research has found that new transit lines can improve travel times for low-income residents (33), however, it is less studied whether travel time savings are equitably distributed across socio-economic strata. For example, Oviedo et al., (34) found that a new BRT corridor in Lima, Peru reduced travel times for commuters overall, but the travel time savings were relatively less for poor areas of the city. This study was conducted in retrospect, rather than evaluating plans currently in development. However, travel time changes are typically output from travel demand models of proposed alternatives included in a cost benefit analysis, meaning their socio-economic distributions could also be analyzed at the planning stage.

Another output of travel demand models are the number of trips by transit, disaggregated as zone-to-zone flow matrices. An increase or decrease in transit use by residents in a neighbourhood can be seen as evidence of improved quality of life for residents. This is because an increase in transit demand indicates that transit has become more attractive (provides a greater utility) than the other modes of travel available, and therefore an increase in transit use means that there has been an increase in traveller utility overall. An increase in transit trips can also indicate mode switching, most likely from driving. The costs of driving are particularly strong for low income households who are usually more sensitive to fuel prices and auto loans (35,36). As such, it would be worthwhile to examine the socioeconomic distribution of new transit travel demand in order to assess who is gaining this utility and reducing their costly auto-based mobility.

Accordingly, the objective of this paper is to examine how the benefits of proposed transit investments, both in terms of opportunity and outcome, are distributed across socio-economic strata. This is exemplified for a proposed rapid transit line in Toronto, Canada.

STUDY AREA & DATA

This study uses data from the Greater Toronto and Hamilton Area (GTHA) to exemplify how the differences in benefits from a new transit line are distributed across a range of relevant social and economic groups. The GTHA is the largest urban region in Canada, with a population of 6,954,000 in 2016. The region will continue to grow, with a projected population of over 10 million in 2041 (5). The GTHA has also witnessed increasing rates of income inequality and socio-spatial polarization over the past several decades (37,38), which has raised concern over unfair distributions of transit service and that limited public transit is a barrier for many to access daily activities (7,39,40).

There are nine local public transit operators in the GTHA, each of which primarily plan and operate surface transit routes. The largest is the TTC (Toronto Transit Commission), the public transit agency for the City of Toronto, which at the time of this study, operates four rapid transit lines, with an additional 25 stop LRT line to come online in 2021. There is also a regional public transit agency, Metrolinx, which runs regional commuter rail and bus routes across the GTHA. Metrolinx, which was formed in 2006 by the province of Ontario, also authors regional transport plans and leads the planning and procurement of major transit projects, such as new BRT, LRT, rapid transit, and regional rail infrastructure in the GTHA (41,42).

One such project is the Ontario Line (OL), a proposed rapid transit line set within the City of Toronto. The proposed alignment and station locations of the OL are displayed in Figure 1, overlaid on a projected population density map for 2041. Proposed plans for a rapid transit route along the approximate alignment of the OL date back for more than 100 years (43), but has remained unbuilt due to fluctuating political support and a failing to secure funding. The current iteration of this plan was announced in early 2019 by the provincial government, replacing previous early-stage planning by the City of Toronto. In July, 2019, Metrolinx released its Initial Business Case study of the OL, ultimately recommending advancing it's design and construction (5).

To conduct our analysis of the OL, we acquired two 2041 demand, travel time, and land-use scenarios developed by Metrolinx in their Initial Business Case (IBC) of the OL (5). These two scenarios are the OL case and the do nothing case, hereafter referred to as the Business as Usual (BAU) case. The scenarios were developed using the Greater Golden Horseshoe Model Version 4 (GGHMv4), an EMME based model used by regional transportation planners for macro travel demand forecasting (44). The OL and BAU scenarios share the same forecasted 2041 land use distributions of population, employment by NAICS and NOCS codes, and student counts by level of education. All data were provided at the Traffic Analysis Zone (TAZ) level of aggregation, including zone-to-zone transit travel times, $T_{i,j} = \{t_{i,j}\}$, and morning peak (6:45am and 8:45am) travel flows by transit, $F_{i,j} = \{f_{i,j}\}$. $t_{i,j}$ are perceived travel times, which include additional weights (a factor 2.5) applied to ingress/egress, waiting, and transfer times. This reflects the relative disutility of time spent walking and waiting compared to time spent travelling in-vehicle, and is a standard approach to modelling travel costs on a transit network (45)

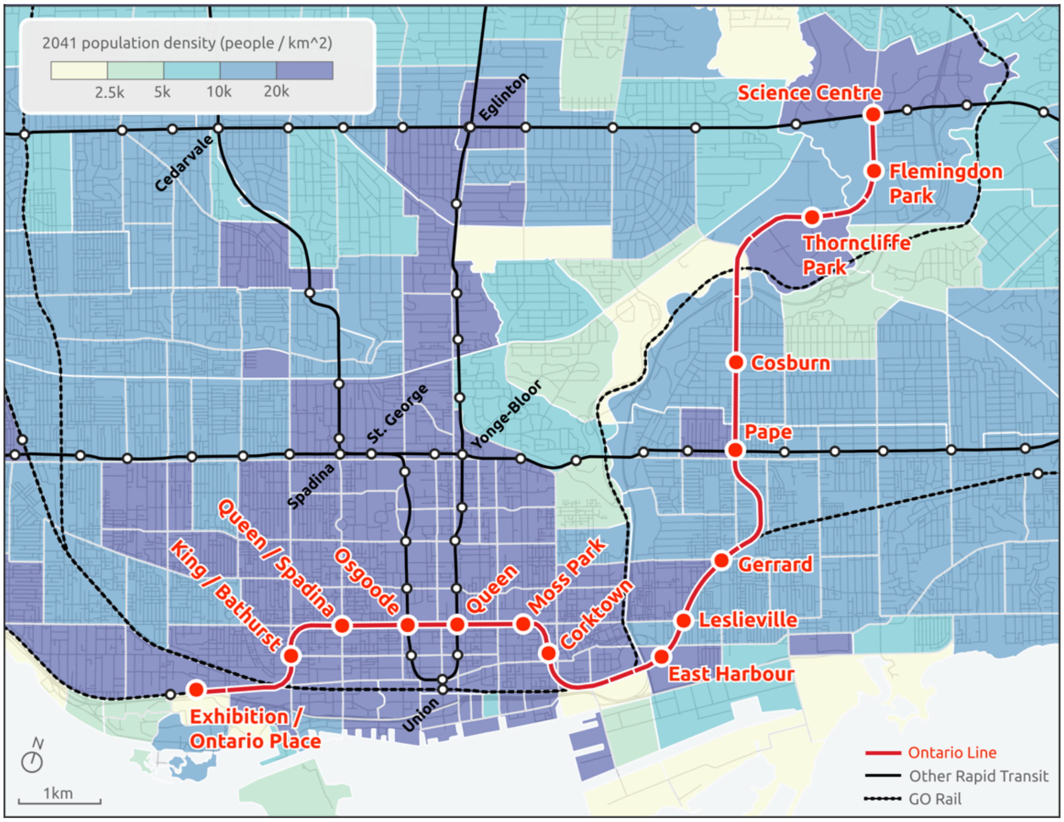

Figure 1 Alignment of the Ontario Line and forecasted 2041 population density

In addition, we use data from the 2016 Canadian census to assess the spatial distribution of different socioeconomic groups. Specifically, we use five categories of socioeconomic status, which have been used previously to examine social polarization (37,46), and in particular, the links between public transit and social deprivation (21,22). These are 1) the percent of the labour force that is unemployed, 2) percent of the population living under the after-tax Low Income Measure (LIM), 3) percent of the population living under the after-tax Low Income Cut-off (LICO), 4) percent of the population identifying as a visible minority, and 5) percent of the population who is a recent immigrant (immigrated between 2011 and 2016). The LIM pertains to households which have less than half the median household income, adjusted by household size; while the LICO pertains to households which are likely to spend 20% more of their income than the average family on housing, food, and clothing (47). Figure 2 shows the alignment of the OL in relation to the 2016 distribution of LIM populations. These socioeconomic data are also used to describe forecasted TAZ population characteristics. In other words, if a TAZ is 50% visible minority according to the 2016 census, then 50% of the TAZ's forecasted 2041 population is assumed to be a visible minority as well. The demographic models used in the GGHMv4 allow for overall population growth, but not changes in the composition of pertinent socioeconomic characteristics of the population.

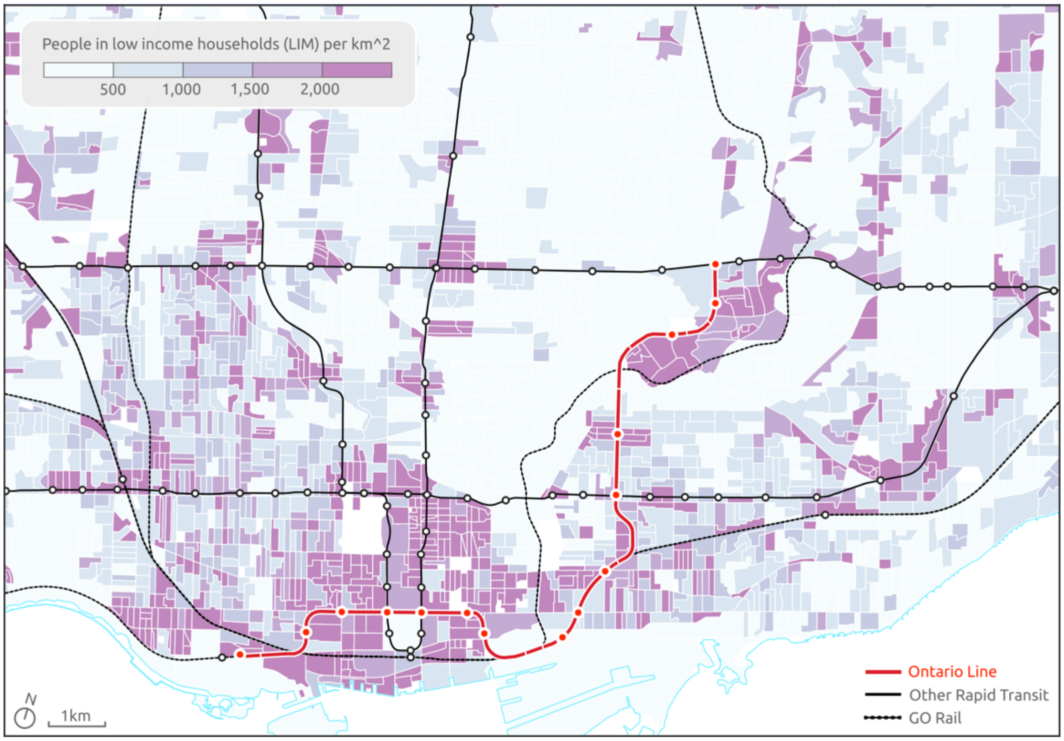

Figure 2 Alignment of the Ontario Line and density of low income households (LIM) in 2016

Lastly we used walking network data to generate station catchment areas. Data for this were walking path networks from OpenStreetMap, with some minor edits near the East Harbour and Exhibition stations to account for proposed paths and streets. Areal apportionment was required to assign census-based Dissemination Area (DA) data to TAZs and to walking catchment buffers. Population-based census data were linked to walking buffers and to TAZs via a block-weighted areal interpolation process (48). This is done first by allocating population into census blocks and then accumulating the intersecting area into the target geographies (in this case, TAZs and walking buffers), weighting by block-level population. Employment data was linked via an area-weighted interpolation procedure since block-level employment counts are unavailable

The results for each subset of our analysis are summarized by impacts for the GTHA, the City of Toronto, as well as for a 5km buffer surrounding the Ontario Line stations. This catchment is based on a 5km Euclidean distance, and TAZs are included in the catchment if at least 50% of a TAZ's area falls within. This accounts for 36% (228/631) of TAZs in the City of Toronto, and 10% (228/2265) of TAZs in the GTHA.

METHODS & RESULTS

Access to Transit Stations

This section provides estimates for the socioeconomic status of the population that is projected to gain walking-distance access to rapid transit due to the construction of the Ontario Line. Figure 3 shows the locations of the stations surrounded by 400m, 800m, and 1200m walking buffers. The 800m buffer is assumed to represent a 10 minute walking catchment using a walking speed of 4.8 km/hr along the pedestrian network from OpenStreetMap. The figure also denotes the difference between walking buffers that have pre-existing access to rapid transit lines. In this analysis, the populations residing in the green catchments are those who are projected to gain walking access to rapid transit exclusively due to the Ontario Line.

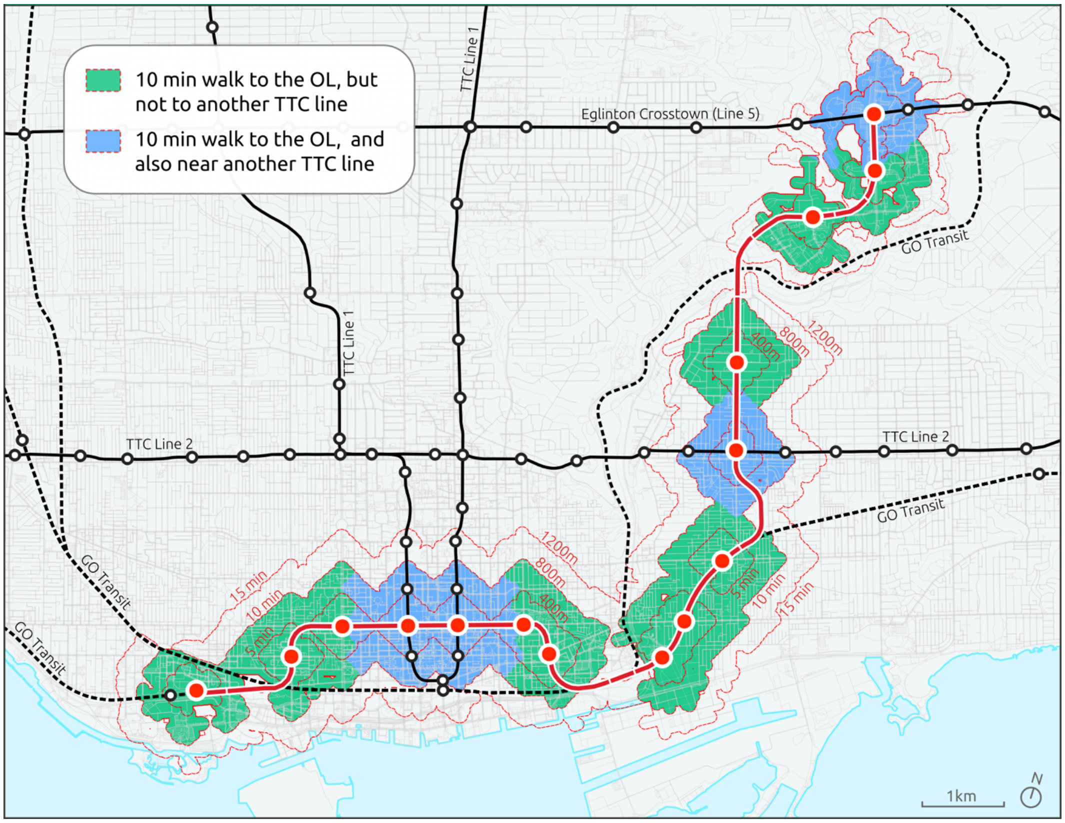

Figure 3 Station catchment areas of the OL

TABLE 1 Distribution of access to transit benefits for different SES groups

		10 Minute Walk to OL (800m)			
		All Stations	New Stations	Toronto	GTHA
Population (2041 projected)	Total	242,000	160,000	3,492,000	10,097,000
Population (2016)	Total	167,000	116,000	2,732,000	6,954,000
Unemployed	Total	7,000	4,900	122,300	289,000
	Percent	**6.7%**	**6.8%**	**8.2%**	**7.7%**
Low Income Cut-Off (LICO)	Total	36,200	25,800	469,300	844,100
	Percent	**22.2%**	**22.8%**	**17.4%**	**12.3%**
Low Income Measure (LIM)	Total	40,500	29,300	543,400	1,039,300
	Percent	**24.8%**	**25.8%**	**20.2%**	**15.1%**
Visible Minority	Total	76,300	53,300	1,385,900	3,194,000
	Percent	**46.7%**	**47.0%**	**51.5%**	**46.5%**
Recent Immigrant (2011-2016)	Total	11,000	8,100	188,000	377,400
	Percent	**6.7%**	**7.1%**	**7.0%**	**5.5%**

Note: the percentages above are based on the category (e.g. unemployed / labour force instead of unemployed / total population)

Table 1 presents population and socioeconomic characteristics of the population residing in the catchment areas. Since the sociocenomic data are provided in the 2016 census, we have tabulated the results according to the 2016 population counts in each catchment. The forecasted results would be nearly equivalent since they would be based on applying 2016 breakdowns to 2041 total population estimates. Table 1 shows a clear pattern that the Ontario Line serves a larger than expected number of low-income individuals compared to the City of Toronto and the GTHA overall. However, the catchment population characteristics for visible minorities and recent immigrants are very similar to the overall averages for Toronto and the GTHA, and there are relatively fewer unemployed people near the stations

The distribution of the low-income population by station area is further illustrated Figure 4. For these lollipop plots, the length indicates the number of people living in households below the LIM, while the colour denotes the percent. Clearly, Moss Park, Thorncliffe Park, and Flemingdon Park stations are serving high amounts of low-income residents. Also notable is that a few other downtown stations will likely serve large numbers of low-income residents, despite these areas being more mixed, in general, compared to those previously mentioned.

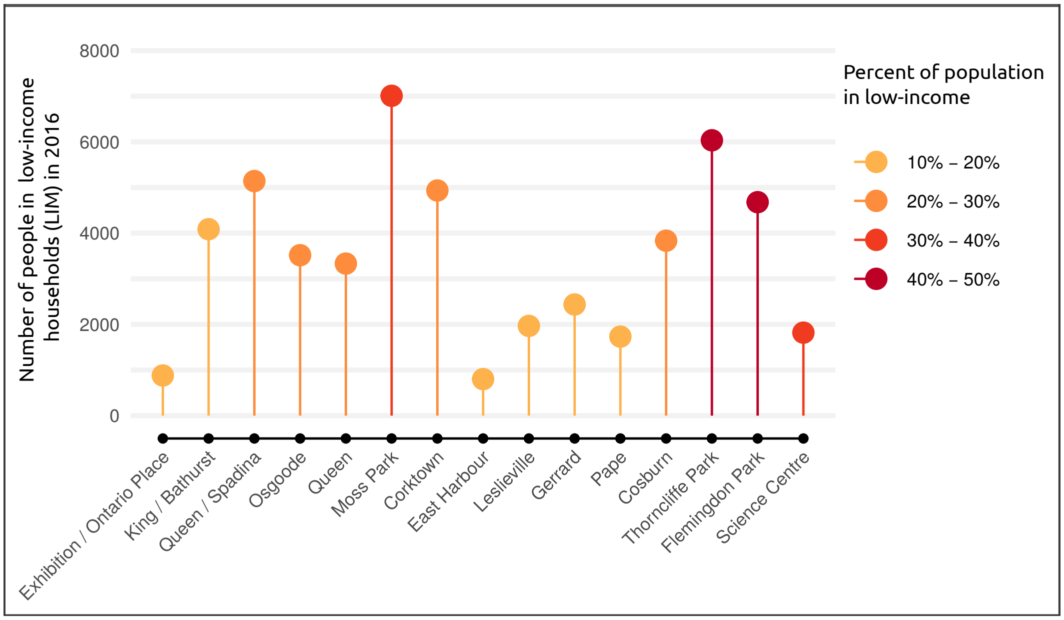

Figure 4 Low income prevalence within a 10 minute walk to OL stations

Access to Destinations by Transit

Accessibility is a measure used in transportation planning to denote the level of opportunity available for residents to reach meaningful activity destinations in their city. It can be conceptualized as the degree of benefit provided to residents by the transportation/land-use system, as a measure of opportunity, and as a measure of freedom to select from a broad set of activity destinations (18,19).

We operationalize accessibility into a gravity model by counting the number of destinations reachable from each neighbourhood in a region, discounting those destinations by the costs of travelling there:

$$A_i = \sum_j O_j f(t_{ij})$$

where t_{ij} is the perceived travel time from zone i to j, O_j is a count of opportunities in zone j, and $f(t_{ij})$ is a distance decay function. The selection of opportunities and type of decay function varies widely in the literature (18,19). For this study we have the projected counts of population, educational, and employment opportunities within each TAZ from the GGHMv4 model, and use them accordingly to measure the impacts of the OL on increasing access to these types of destinations. In this study we draw t_{ij} from the perceived travel time matrices generated by the GGHMv4 model, and apply a decay weight empirically calibrated against the cumulative distribution function (CDF) of observed trips in the BAU GGHMv4 demand matrix:

$$f(t_{ij}) = 1 - \mathrm{CDF}(t_{ij}).$$

The BAU scenario was selected because it produces weights with a slightly flatter decay than the OL scenario. It can be interpreted as being a more conservative choice since it provides a slight accessibility advantage to the BAU case. The travel time matrix was also subset for just trips in the City of Toronto, which is more representative of the types of transit trips used by the Ontario Line compared to those across the entire GTHA. Figure 5 depicts the generated distance decay function. The curve provides the weight, between 0 and 1, that is applied to trips at each perceived travel time. In this way, nearby destinations receive weights closer to 1, while trips further away approach weights close to zero. It is important to recall that these are perceived transit travel times, which, because of the weights placed on walking and waiting times, are larger than actual door-to-door travel times. They are, however, assumed to be a more relevant predictor of travel behaviour.

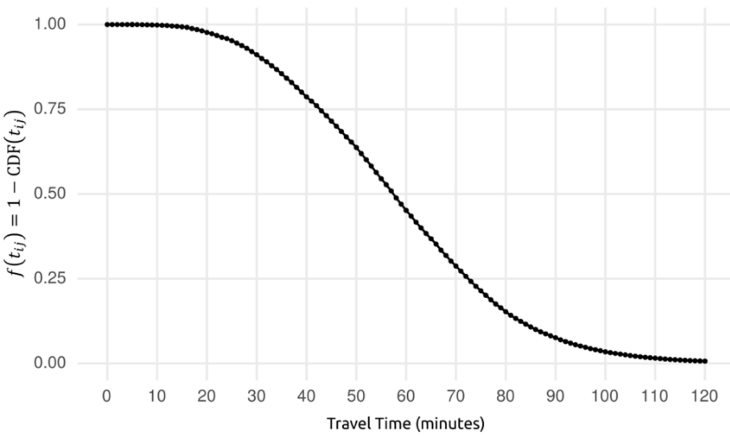

Figure 5 Estimated decay curve for accessibility calculations

A map of access to education appears in Figure 6, and a table of results disaggregated by socioeconomic status is provided in Table 2. We observe large accessibility gains for TAZs abutting the Ontario Line, especially those at the two extremities of the line, for which trips to the universities and colleges downtown will become significantly shorter. We also observe large accessibility gains in TAZs southeast of the main bend as the OL will provide improvements in access to downtown educational opportunities. According to the results in Table 2, the educational access benefits are slightly more concentrated in low-income, visible minority, and recent immigrant populations, especially among the TAZs within a 5km buffer of the OL Stations.

Access to employment is a widely used measure to evaluate the distribution of benefits of transit infrastructure (19). An access to employment score can be interpreted both as an economic indicator, since access to employment is a pathway to making labour markets more efficient, as well as a general indicator of access to destinations via transit, since spatial distributions of employment proxy the spatial distributions of many types of activity destinations of interest to residents (e.g. retail, services, healthcare, etc.). The spatial and socioeconomic distributions of employment accessibility largely replicate those found for education above. However, the scale of improvement for jobs accessibility is higher, likely because employment is more concentrated than education, given the distribution of K-12 institutions being evenly dispersed into residential neighbourhoods. Overall, access to employment is improved throughout Toronto because of the Ontario Line, with benefits accruing to low-income, visible minority, and recent immigrant groups, more than the overall population.

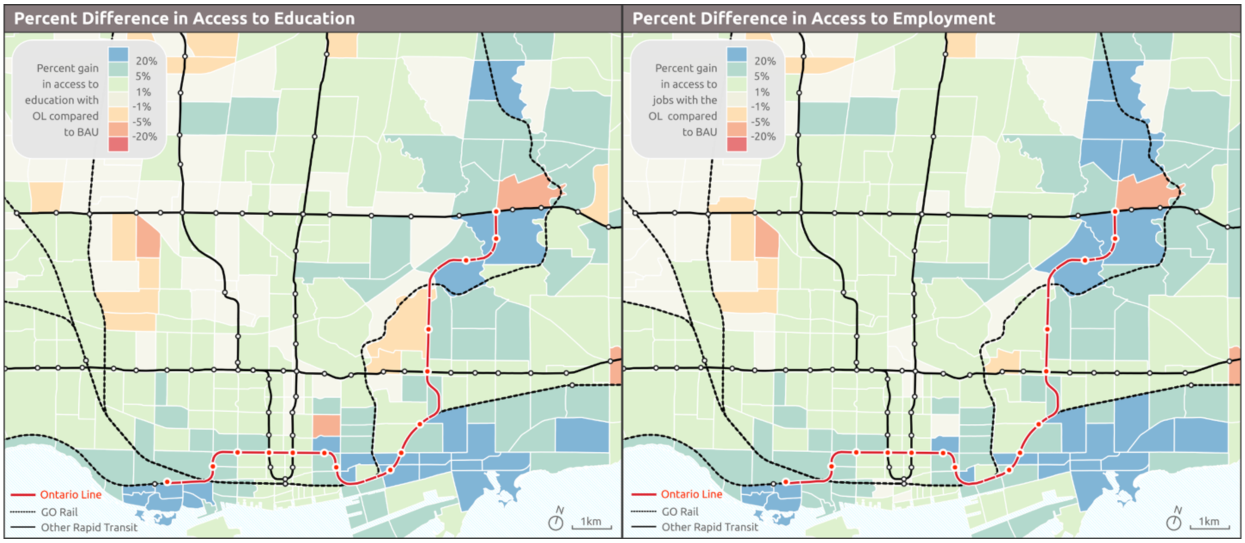

Figure 6 Percent difference in access to education (left) and access to employment (right) with and without the OL

TABLE 2 Percent difference in access to destinations, disaggregated by SES

		Percent Increase in Access to Destinations (2041)		
		GTHA	City of Toronto	5km of OL
Access to Education	Overall Population	1.1 %	3.3 %	6.7 %
	Unemployed	1.2 %	3.2 %	6.8 %
	Low Income Cut-Off (LICO)	2.0 %	3.7 %	7.6 %
	Low Income Measure (LIM)	1.8 %	3.7 %	7.9 %
	Visible Minority	1.3 %	3.1 %	8.2 %
	Recent Immigrant (2011-2016)	1.6 %	3.3 %	8.0 %
Access to Employment	Overall Population	0.9 %	3.3 %	7.1 %
	Unemployed	1.0 %	3.3 %	7.5 %
	Low Income Cut-Off (LICO)	1.9 %	3.8 %	8.2 %
	Low Income Measure (LIM)	1.8 %	3.8 %	8.7 %
	Visible Minority	1.1 %	3.1 %	9.0 %
	Recent Immigrant (2011-2016)	1.6 %	3.4 %	8.9 %
Access to Low-Income Employment	Overall Population	0.9 %	3.3 %	7.2 %
	Unemployed	1.0 %	3.3 %	7.6 %
	Low Income Cut-Off (LICO)	1.9 %	3.8 %	8.2 %
	Low Income Measure (LIM)	1.8 %	3.9 %	8.7 %
	Visible Minority	1.1 %	3.2 %	9.1 %
	Recent Immigrant (2011-2016)	1.6 %	3.5 %	8.9 %

One of the common criticisms for the use of total employment counts in the study of jobs accessibility, especially for low-income populations, is that many jobs being counted in the access score may be unattainable to low-income populations due to a mismatch with skills and training. To overcome this challenge, it is becoming more common for researchers to present access scores to a selection of jobs that are deemed more relevant to the populations of interest (21,26). In this study, we make use of Statistics Canada cross-tabulations of number of jobs by National Occupational Classification (NOC) and low-income status (based on the LIM). Statistics Canada provides the percentage of low-income workers in Toronto who are employed in each occupational classification (49). We incorporate these percentages as additional weights on $O_{c,j}$, the number of jobs in zone j of type c, giving higher weight to jobs that low-income workers are more likely to have, and lower weights to jobs that are less prevalent among low-income workers.

$$A_i = \sum_{c \in C} \sum_{j \in J} w_c O_{c,j} f(t_{ij})$$

Where w_c is the weight applied to each occupation class, ranging from 0 (no jobs in this class are low-income) to 1 (where all jobs are low-income jobs). Results for these accessibility scores are also presented in Table 2. Immediately evident from these tables is that the patterns of low-income jobs accessibility are very similar to the pattern for total employment. Either the values are the same, or 0.1% greater than above. The map for access to low-income employment was equivilant to access to all employment, so it is not included for the sake of brevity.

Travel Times

In this section we present the results pertaining to the differences in travel time in the region that are projected to occur due to the Ontario Line. Travel times are weighted by the projected number of transit trips for each pair of TAZs. This is computed as follows from the output of the travel demand model.

$$\Delta_i = \frac{\sum_j f_{ij}^{OL} t_{ij}^{OL}}{\sum_j f_{ij}^{OL}} - \frac{\sum_j f_{ij}^{BAU} t_{ij}^{BAU}}{\sum_j f_{ij}^{BAU}}$$

where Δ_i is the weighted mean travel time difference for a zone, i. t_{ij}^{OL} and t_{ij}^{BAU} are the travel times from zone i to zone j for the OL and BAU scenarios respectively. f_{ij} is the number of transit trips between zones i and j, and all other terms are defined as before. The superscripts on the flow terms also denote the scenario from which they are drawn. Negative values of Δ_i denote a reduction in average travel time from zone, i, to all other zones in the region. A map of the weighted travel time differences between the two scenarios is shown in Figure 7. As expected, most of the zones near the new infrastructure experience travel time savings.

TABLE 3 Average Travel Time Savings in Minutes and Percentages for 2041 Populations by SES

	GTHA		City of Toronto		5km of OL	
	Minutes	Percent	Minutes	Percent	Minutes	Percent
Overall Population	0.69	0.71	1.09	1.75	1.76	3.19
Unemployed	0.65	0.72	1.05	1.69	1.72	3.14
Low Income Cut-Off (LICO)	1.03	1.37	1.20	1.97	1.84	3.42
Low Income Measure (LIM)	0.98	1.21	1.21	1.98	1.94	3.59
Visible Minority	0.86	0.97	1.08	1.69	2.04	3.71
Recent Immigrant (2011-2016)	0.87	1.08	1.00	1.60	1.91	3.47

The travel time differences for each zone are averaged according to the overall population as well their socioeconomic characteristics. This is presented in Table 3 in terms of average reductions in travel time for each population group across the GTHA, within the City of Toronto, and then for the populations residing in TAZs within 5km of the Ontario Line. The table illustrates that low-income populations are likely to see more reduction in transit travel time than the Toronto population on average. Other population groups appear to obtain similar improvements to the overall population in Toronto, mirroring the results found above regarding the catchment area population characteristics (being similar to the average characteristics of the City of Toronto). Within the 5km catchment however, visible minorities and recent immigrants are projected to have larger reductions in travel times than the overall population living within the buffer. This makes sense as large swathes of the 5km buffer include affluent central neighbourhoods whose travel times seldom would be impacted by the new services provided by the Ontario Line.

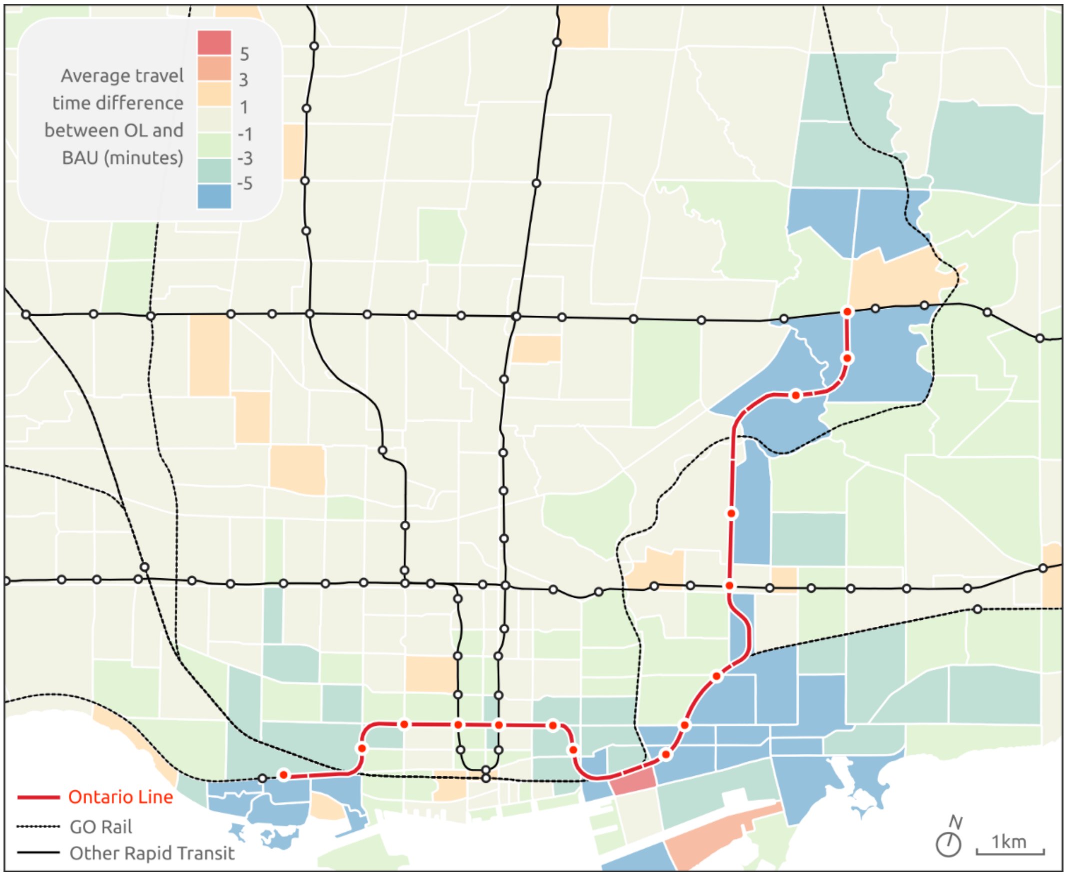

Figure 7 Map of flow-weighted travel time differences

Demand Differentials

In this section, we present on the differences in overall number of transit trips being projected by the GGHMv4 model between the BAU and OL scenarios. We interpret an increase in transit use by residents in a zone as evidence of improved quality of life for residents there. An increase in transit demand indicates that transit has become more attractive (provides a greater utility) than the other modes of travel available, and therefore an increase in transit use means that there has been an increase in traveller utility. The patterns of increased travel demand in Figure 8, and the socioeconomic distribution of this demand increase in Table 4.

The map of new demand clearly shows that the OL will make transit a more attractive choice for hundreds of trips per TAZ in zones served by the infrastructure, including locations connecting to the OL via other transit modes (e.g. particularly along east-west streetcar routes). According to the travel demand matrices, the OL induces more than 15,000 peak period transit trips, compared to the BAU scenario, and these are being concentrated in TAZs served by the OL. Based on the neighbourhood characteristics of the TAZs receiving transit demand growth, we estimate that nearly 20% of these trips are being performed by low-income residents, slightly more than the population make-up of the region. However relatively fewer trips are being made by unemployed, visible minority, and recent immigrant populations.

TABLE 4 Average Travel Time Savings in Minutes and Percentages for 2041 Populations by SES

	New Transit Demand (2041)		Toronto (2016)	GTHA (2016)
	Trips	Percent* of Trips	Percent* of Population	Percent* of Population
Overall Population	15,259			
Unemployed	639	4.9%	8.2%	7.7%
Low Income Cut-Off (LICO)	2,663	17.9%	17.4%	12.3%
Low Income Measure (LIM)	3,037	20.4%	20.2%	15.1%
Visible Minority	6,099	40.9%	51.5%	46.5%
Recent Immigrant (2011-2016)	806	5.4%	7.0%	5.5%

*based on sub-group that each belongs to (e.g. private households, labour force, etc.), not the overall population.

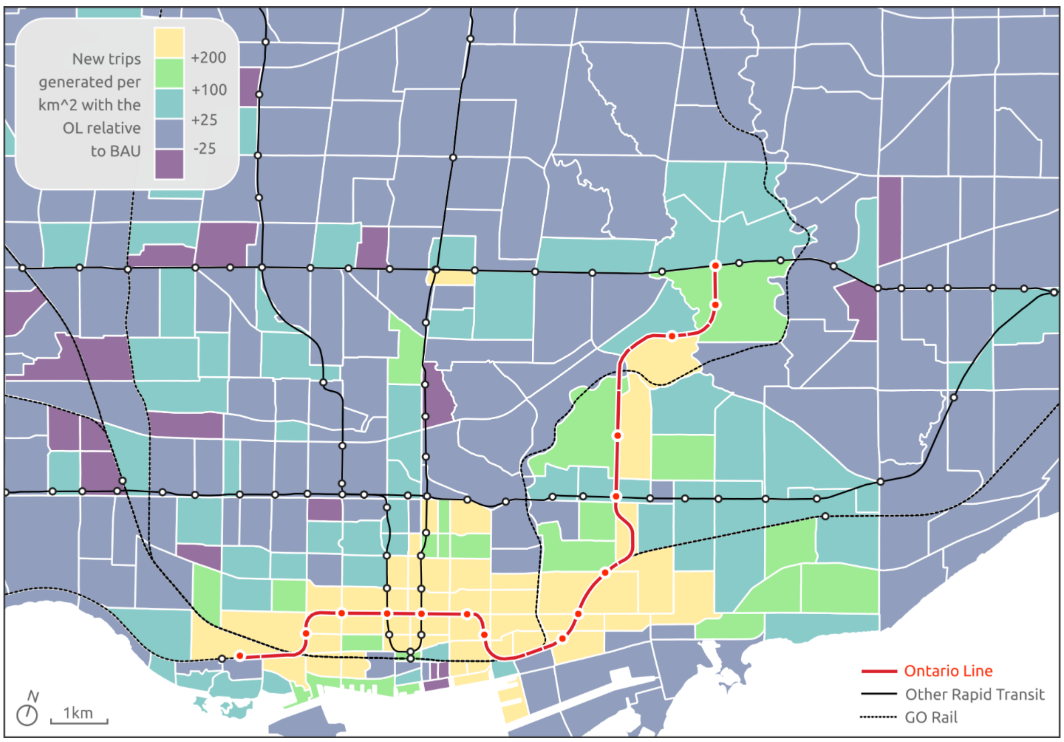

Figure 8 Change in Transit Travel Demand between the BAU and OL Scenarios

Sensitivity to Population Dynamics

The zone-based population projections that were available for this study (like many population projections used for transport-land use modelling) do not provide breakdowns of population by SES. As such, our analysis above had to rely on current distributions of SES and apply them to 2041 population and household count forecasts. Even in studies that have socio-economic population forecasts available, they are usually limited to only a single future population scenario (50). However, it is well known that the social geographies of cities are not static (37,38,48). Toronto, similar to other cities, has witnessed trends of socio-spatial polarization (38), and suburbanization of poverty over the past several decades (37). As well, previous research has noted that transit investments can in some cases drive up land values (51), potentially pushing low-income households to move to less accessible, but more affordable neighbourhoods (52). Conversely, progressive urban housing policy could plan for social housing and other types of affordable housing to concentrate in areas of high transit accessibility (53). As such, we account for uncertainty in future population dynamics by conducting a sensitivity analysis of our results based on three different scenarios of changing patterns of income distribution in the region.

1. Continued income polarization and segregation of poverty based on the current distribution of low-income households. i.e. low income TAZs continue to get poorer, while wealthier TAZs see reductions in their poverty rates.
2. Gentrification of TAZs with above-average levels of transit accessibility, causing low income households to concentrate in TAZs with low transit accessibility.
3. TAZs with above average transit accessibility are earmarked for housing that is affordable for low-income residents (e.g. social housing), causing low-income households concentrate in areas with high transit accessibility rather than areas with low transit accessibility (i.e. the opposite to the gentrification scenario).

For each of these scenarios, we begin with a baseline case, where the low-income population in each TAZ in 2041 is determined by the current low-income rate and the projected total population for the TAZ. Then, for each iteration, 1,000 low income residents are re-sorted from TAZs classified as X to TAZs classified as Y, where sorting is constrained by the total projected population in each zone. This process assumes that the overall number and rate of low-income residents in the region remains constant; only their distribution among TAZs changes. For the increased poverty segregation scenario, X and Y, are TAZs with currently below and above average levels of poverty (by LIM) in Toronto (20.2%), respectively. For the increased transit-induced gentrification scenario, TAZs are classified as X and Y based on whether they are above and below the mean level of transit accessibility (in the City of Toronto). The affordable near transit scenario is simply the opposite of the gentrification scenario (low transit access areas X and high transit access areas are Y). For each iteration, we compute the mean level of transit accessibility for low income residents, $\bar{A}_{LIM}$, and the mean level of transit accessibility for residents not in low income households, $\bar{A}_{LIM^c}$. We then compute a ratio of these two means, which provides a sense of how equitable the distribution of transit accessibility is.

$$R_A = \bar{A}_{LIM}/\bar{A}_{LIM^c}$$

If R_A is greater than 1, then transit accessibility is servicing low-income residents more so than non-low-income residents. Figure 9 (left) displays the results for access to employment for 200 iterations (up to 200,000 low-income residents being re-distributed) and for each of the three income segregation scenarios. The results were very similar between the OL and BAU cases, so Figure 9 (left) only shows the result for the OL case. Figure 9 (right) displays a similar plot, but for the ratio of travel time savings between low-income and non-low-income residents

$$R_\Delta = \bar{\Delta}_{LIM}/\bar{\Delta}_{LIM^c}$$

The two plots tell a similar story. First, if low-income residents continue to concentrate where there are already high rates of low-income households (i.e. continued polarization), it will have little bearing on changes in the overall equity of transit provision. If land development in high transit accessibility areas is earmarked for low-income housing, then, as expected, low-income residents will have relatively greater levels of transit accessibility to non-low income residents, as well as witness a greater benefit from the OL in terms of travel time savings. Opposite to this, if there are continued trends of gentrification, then the vertical equity of transit provision will decrease. An interesting point is where the gentrification line intersects with R = 1. This can be considered the tipping point to where transit provision becomes vertically inequitable. In terms of accessibility, this occurs when 44,000 low income residents are sorted from areas of high transit accessibility to areas of low transit accessibility. With regards to travel time benefits between the BAU and OL (Figure 9 right), this point occurs when 117,000 low income residents are sorted from areas of high transit accessibility to areas of low transit accessibility. For context, there are will be an estimated 350,000 low-income residents living in areas of more than average levels of transit accessibility in 2041 presuming the overall share of low-income residents does not change from today's rates.

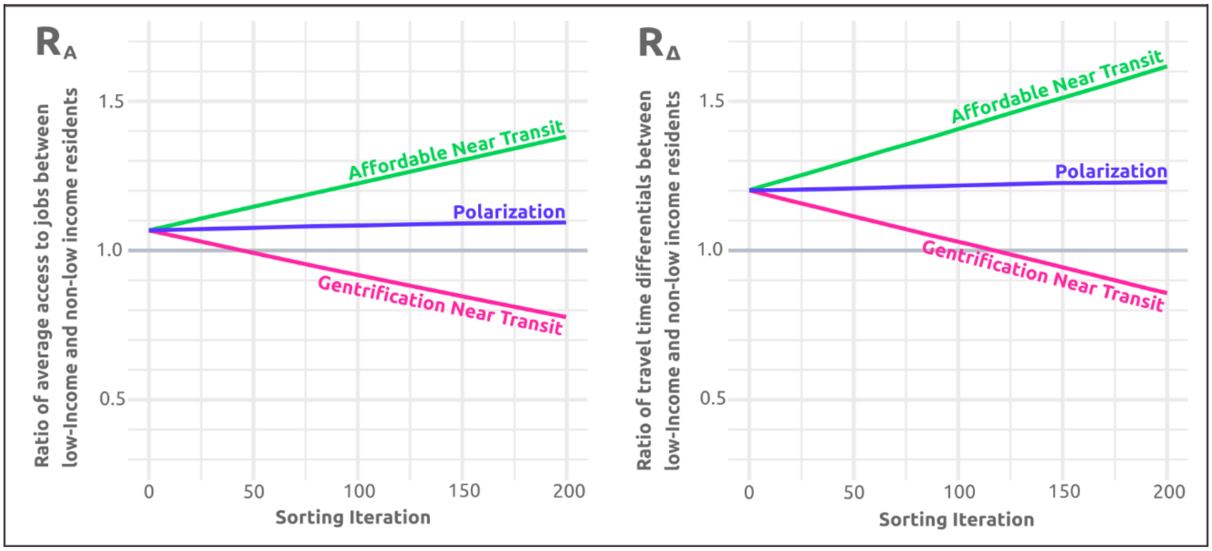

Figure 9 Differentiation of results for three income segregation of scenarios

CONCLUSIONS

In this paper, we outlined and exemplified a procedure for evaluating the socioeconomic distribution of benefits resulting from a new transit line. This was applied to the Ontario Line (OL) in Toronto, Canada. We find that overall, benefits of the OL are slightly more concentrated towards low-income households, relative to the overall population.

According to where low-income households live today, about 25% of the population within walking distance of OL stations will be in-low income households. As well, gains in transit-based access to destinations will be 1%-1.5% greater for low-income households than the overall population. Visible minority, unemployed, and recent immigrant populations also achieve similar gains in transit-based access to destinations. Overall, we find that access to education and jobs via transit will improve more than 20% for many residents living in zones near the OL. These results indicate that the benefits of the OL are distributed equitably and without discrimination.

Results are mixed in terms of outcome based benefits. Results for travel time reductions are positive; we find that all socioeconomic groups will achieve reductions in travel times with the OL, slightly more than the overall population on average. The OL line is also expected to generate 15,000 new transit trips per morning commute period in the region, but relatively few of these transit trips are made by unemployed, visible minority, and recent immigrants. This could be because many of these people are already taking transit, and the travel demand model is only considering new transit trips resulting from mode-switching. As such, one direction for work would be to incorporate into the analysis how increased transit accessibility has the ability increase trip and activity generation rates (7).

Similarly, another limitation of this work is that the travel demand model outputs in which we had access to only considered the morning commute period. However, previous studies have noted that low-income workers tend to have less regular commuting patterns (21). It could be that our analysis is in fact under-estimating benefits for low-SES residents if the gap in off-peak travel times and access to destinations is greater than during peak periods. Indeed, an important direction for future work would be to generate and analyze a more comprehensive set travel time and demand options for different times of day and week (e.g. week versus weekend).

Thirdly, our analysis used the same land-use population and employment forecasts for both scenarios. However, it is likely that the construction of new rapid transit stations would spur urban development in the areas adjacent to them (8). This could have several effects. First, there would likely be further increases in accessibility for the residents near stations as there would be more nearby employment opportunities and activity destinations that do not require longer transit trips. For example, the three northern stations on the OL, which have the greatest concentration of low-SES households, also have swaths of redevelopable land available. This signifies opportunity for commercial intensification in these station areas, and if implemented responsibly, could add substantially to the livability of these neighbourhoods and its residents, particularly if new development incorporates housing for low income residents. Conversely, this could increase land values (51), potentially pushing low-income households to move to less accessible, but more affordable neighbourhoods (52).

The sensitivity analysis in the previous section notes that if transit-induced gentrification occurs, that the travel time benefits of the OL, as well as the overall geography of transit accessibility in the region, are no longer vertically equitable. This is an important finding, as the majority of accessibility/equity studies today fail to incorporate social dynamics in their evaluations, despite population dynamics really governing whether a specific project will be equitable or not. Accordingly, future work should also include more detailed demand modelling and population forecasting to incorporate a wider range of development scenarios, socioeconomic variables, and their temporal dynamics.

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AUTHOR CONTRIBUTIONS
The authors confirm contribution to the paper as follows: study conception and design: J. Allen, S. Farber; data collection: J. Allen, S. Farber; analysis and interpretation of results: J. Allen, S. Farber; draft manuscript preparation: J. Allen. All authors reviewed the results and approved the final version of the manuscript.

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